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ASRDI OXYGEN

TECHNOLOGY SURVEY

Volume V: Density and Liquid Level Measurement

Instrumentation for the Cryogenic Fluids

Oxygen, Hydrogen, and Nitrogen

RODER



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Oxygen, Hydrogen, and Nitrogen

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PREFACE

This publication is part of an oxygen safety review in progress by the NASA Aerospace Safety Research and Data Institute (ASRDI). The objectives of the review include:

1. Recommendations to improve NASA oxygen handling practices by comparing NASA and contractor oxygen systems including the design, inspection, operation, maintenance and emergency procedures.
2. Assessment of the vulnerability to failure of oxygen equipment from a variety of sources so that hazards may be defined and remedial measures formulated.
3. Contributions to safe oxygen handling techniques through research.
4. Formulation of criteria and standards on all aspects of oxygen handling, storage, and disposal.

This special publication reviews the present state of instrumentation for density and liquid level measurements in oxygen. Since the volume of literature dealing specifically with oxygen instrumentation is very limited the author has included information relating to other cryogens where there was potential usefulness to oxygen systems. This survey includes a survey of instrument types as well as examples and a special section covers zero g instrumentation. Of special interest is a table developed by the author which summarizes the various instrumentation types. The report also presents a discussion of problem areas in density and liquid level measurement and recommends areas for further research and development.

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1. Introduction

This volume of the survey presents information on instrumentation for density measurement, liquid level measurement, quantity gaging, and phase measurement. Of the documents reviewed and evaluated for inclusion in this publication coverage of existing information directly concerned with oxygen was given primary emphasis. However, work not specifically designated for oxygen, but considered of potential value in oxygen service is included occasionally as an aid to the reader.

Instrumentation for cryogenic systems generally has been developed from more conventional, higher temperature systems. Measurement devices (sensors), as a whole, have not been developed for a particular low temperature application, but instead have been forced to cope with the cryogenic environment. A result has been the use of conventional instruments in perhaps an adequate, but sometimes marginal, manner. For proper application, the properties and peculiarities of the cryogenic fluids themselves must be recognized and understood. For this reason a description of the physical principle of measurement for each instrumentation type is included in section 3 of the report. For actual values of the properties involved the reader is referred to Volume I of this series, Thermophysical Properties [80838].

Many materials of construction used in conventional devices are not compatible with dense gaseous or liquid oxygen. For that reason we list the basic materials of construction if available from the source document for each instrument discussed. Cleanliness is always a factor with instrumentation, but more so in an oxygen environment. The reader is referred to Volume II of this series, Cleaning Requirements, Procedures, and Verification Techniques [V1197].

Intelligent choice of an instrument for a given purpose requires that certain things be known or determined beforehand — i. e., essential accuracy and sensitivity of the instrument; general range of the measurement; necessary ruggedness of the system. A specification that is greater than the requirement can result in unwarranted expense at initial procurement, more frequent and extensive maintenance and calibration procedures than needed for less complex devices, and costly replacement inventories. Conversely, an underspecified instrument may be of even less value, and may suffer, as well, from some of the same problems listed above. As an aid to the reader we list, if they are available from the source documents, precision, accuracy, and sensitivity of the various instrument types.

The present volume is restricted to the static methods of quantity gaging and contains references for each instrument discussed. A companion volume [V1635] treats the dynamic methods of quantity gaging, i. e., flow metering. An excellent survey of high precision laboratory measurement systems has been published by Levelt-Sengers [37520]. A

comprehensive survey of liquid level instrumentation used in chemical processes has been published by Considine [49030]. An elementary discussion which indicates the fundamentals of instrumentation with regard to temperature, pressure, and liquid level (quantity) measuring devices and techniques, together with recommended methods of installation and application is given by Schmidt [70607]. Much of the information on performance characteristics of point sensors is based on a significant experimental effort conducted at the National Bureau of Standards on the liquid level of liquid hydrogen [16980]. The report also presents a discussion of problem areas in density and liquid level measurement, and recommends areas for further research and development.

2. Classification of Instrumentation

2.1 General

The measurement of density, quantity, liquid level, and phase are intimately related, as will be seen from the following discussion. One of the major parameters of interest in systems using liquid oxygen is quantity. The most frequent requirements are the determination of mass in a tank and the determination of mass flow rates into or out of tanks. In either case a knowledge of density is required. One common technique in determining the mass of oxygen in a tank is to measure both the liquid level and the density, this assumes that the tank volume as a function of height is known. Another technique is to simply measure the liquid level and infer the density from auxiliary measurements of pressure and/or temperature, again assuming that the tank volume vs. height is known. Similarly, the mass flow rate of oxygen in a line is most often determined by measuring the volumetric flow rate, and either measuring or inferring the density.

The fact that the volume of a tank must be known is hardly ever stated explicitly in discussions of quantity gaging. We point out here that obtaining the volume of a tank is far from trivial, involving problems of thermal contraction and deformation under load. We also point out that there are two techniques in common use for quantity gaging, direct weighing, and finding density from tables of PVT data if pressure and temperature are known. We will not discuss these techniques since they are not quantity gaging instrumentation per se.

Almost all liquid level devices measure the change in a given property between liquid and gas states. Thus each liquid level device is also a phase or state detector. The change in property is most easily explained in terms of the large density difference which exists between liquid and gas states. Very often a single measurement can be adapted to yield several of the quantities sought, for example a capacitance measurement can yield density, liquid level, or phase. Even the determination of density for the supercritical fluid is the same as finding the phase or state of the gas.

Since the measurement of density, quantity, liquid level and phase are so intimately related the discussion will be presented under the two major headings of density measurement instrumentation and liquid level instrumentation.

2.2 Instrumentation Types

There are a number of ways in which one can classify density and liquid level instrumentation. From the standpoint of applications, categories of instrumentation types are the most useful. These functional categories are listed in table 1, they are used descriptively in the detailed discussion of each instrument in the sections that follow. Note that a given instrument may fill a requirement in more than one category. Also, a number of the more successful liquid level devices can be combined into a rake or a series of point sensors to get an instrument of the continuous variety. Thus the differentiation between point sensors for liquid level and continuous sensors is somewhat arbitrary.

2.3 Classification by Physical Principle

Another way of classifying density and liquid level instrumentation is by the underlying physical principle which is exploited. These principles of measurement are also used descriptively in the detailed discussion of each instrument. They are discussed by classes in section 3.

Density can and is measured in an absolute sense. Consider the basic definition

$$\rho = M/v .$$

To get a density ρ in g/cm^3 we have to measure M a mass in grams, and v a volume in cm^3 . A second way of making highly accurate measurements is by reference to a liquid of known density, say water, using Archimedes' principle. However, measurements of high accuracy, i.e., primary standards accuracy, are normally only made under laboratory conditions. They are shown in table 1 under the heading of "laboratory measurement systems."

The bulk of this report will consider "applied measurement systems" in other words routine measurement instrumentation used in the field, used by industry, or available as an "off the shelf" item of instrumentation. Most practical measurements of density or liquid level exploit a well defined physical relationship, for example the variation of dielectric constant with density. Implied is that the relationship has been measured in a separate, highly accurate laboratory experiment, in other words that appropriate physical properties data are available. Quite often a calibration in terms of a well defined property and/or a specified technique is required for a given instrument. A detailed classification of practical instrumentation according to the physical principle of measurement is given in table 1. Table 1 shows quite clearly that many of the categories which apply to density are equally valid for liquid level.

Table 1. Classification of Density and Liquid Level Instrumentation

Major Breakdown	Density	Liquid Level
Instrumentation Type	density, static density, dynamic density, low or zero "g" density, very low density, supercritical	point sensors continuous sensors
Physical Principles of Measurement		
Laboratory measurement systems	weight and volume buoyancy (Archimedes' principle)	Calibration against visually measured height, or other known geometrical factors
Applied measurement systems	<u>dielectric constant</u> A capacitance B microwave * B1 resonant cavity B2 attenuation B3 phase shift (FDR) B4 transmission time (TDR) C <u>radiation attenuation</u> C1 β or γ or infrared C2 neutron absorption D <u>buoyancy, magnetic plummet</u> E <u>acoustic</u> * E1 reflection E2 magnetostrictive E3 piezoelectric F <u>forced harmonic oscillation</u> F1 vibrating cylinder F1 transverse mode F2 hoop mode F3 vibrating reed F4 paddle wheel Z <u>quantity gaging, zero "g"</u>	<u>dielectric constant</u> A capacitance point, continuous B microwave B1 resonant cavity point B3 phase shift (FDR) continuous B4 transmission time (TDR) continuous C <u>radiation attenuation</u> C1 β or γ point, continuous C2 neutron absorption continuous D <u>mechanical float</u> D1 ball type continuous D2 magnetically sensed continuous E <u>acoustic</u> E1 reflection point E2 magnetostrictive point E3 piezoelectric point, continuous F <u>forced harmonic oscillation</u> F1 vibrating cylinder point F3 vibrating reed point F4 paddle point G <u>pressure</u> G1 differential pressure point, continuous G2 vapor pressure point, continuous G3 gas bubbler point, continuous G4 mercury sealed bell continuous G5 diaphragm box point, continuous H <u>Optical</u> point I <u>heat transfer</u> I1 hot wire point, continuous I2 thermocouple point, continuous I3 semiconductor point, continuous J <u>thermal expansion</u> point

* microwave and acoustic are quite similar, microwave involves frequencies of GHz, while acoustic uses MHz.

2.4. Other Classification Schemes

We could have classified the instruments according to the phase in which they operate, i. e., liquid or compressed fluid, fluid or dense gas, gas or vapor, supercritical, gas at extreme rarefaction, two phases liquid-gas both present, etc. Since in most instances the phase of operation is obvious we indicate it in the detailed discussion of each instrument only for a few selected cases.

3. Survey of Physical Principles

3.1 Laboratory Measurement Systems

The determination of the equation of state of oxygen, that is the dependence of pressure on temperature and density, has been the subject of a large number of papers. We are not going to dwell on laboratory measurements to any extent because several excellent review papers on the subject exist. A survey of PVT measurements from the chemical engineers' point of view has been published by Ellington and Eakin [19637]. Measurement techniques of high precision with emphasis on low temperatures have been discussed in detail by Levelt-Sengers [37520]. The most important information from the latter reference concerns absolute accuracy — "it has proven very hard to surpass the one part in 1000 mark in accuracy of PV data." This means that the state of the art as far as density is concerned is 0.1%. We note this uncertainty in the basic properties data since many of the density measuring devices are calibrated against the "known" value of the saturated liquid. The factor limiting the final accuracy is the volume determination. The laboratory systems are subject to the very considerations that make it difficult to predict the actual volumes of cryogenic tankage, namely thermal contraction of the construction materials which is often anisotropic, and deformation under applied pressure.

We note that pycnometers so often used at room temperature have found some application at low temperatures. Their volumes are determined at room temperature by calibration with mercury of known density. For a low temperature application corrections for thermal contraction must again be applied. A device capable of an absolute density determination is the magnetic densimeter described by Haynes and Stewart [72829]. It is based on Archimedes' buoyancy principle and has been developed commercially.

3.2 Applied Measurement Systems

The order of physical principles follows the arrangement of table 1, that is, first those principles that apply to both density and liquid level, and then those that apply only to liquid level instrumentation.

A. Dielectric Constant, Capacitance

For a liquid composed of spherical, non-polar molecules, the Clausius-Mossotti equation relates the dielectric constant to the density as follows:

$$\frac{\epsilon - 1}{\epsilon + 2} = \frac{4\pi N\chi}{3M} \quad d = \rho$$

where ϵ = relative dielectric constant

M = molecular weight

N = Avogadro's number

d = density

χ = polarizability of the molecule

P = molecular polarization

For oxygen measurements of very high precision the C-M relationship has to be extended to a working relation of

$$\frac{\epsilon - 1}{\epsilon + 2} = A\rho + B\rho^2 + C\rho^3$$

where A , B and C are simply coefficients. Capacitors are used to measure the dielectric constant. Capacitor configurations used vary, but parallel plates or concentric cylinders are common. The relationship between dielectric constant and capacitance is particularly simple for a parallel plate capacitor:

$$C = 0.0885 \epsilon S/l$$

where C = capacitance, pf

S = surface area of the capacitor cm^2

ϵ = dielectric constant

l = distance between the plates cm

Capacitance readings are affected by the thermal contraction of plates and spacers used, in addition stray capacitance is often a problem. A calculation of potential error for a parallel plate capacitor in liquid hydrogen from thermal contraction of the spacer yields a calibration error of about 0.4% [24998]. It is clear, therefore, that in almost all cases capacitance devices have to be calibrated.

For liquid level applications see also general discussion on page 29.

B. Dielectric Constant, Microwave

B1. Resonant Cavity

The shift in resonant frequency when a gas is introduced into an evacuated microwave cavity gives a measure of the dielectric constant of the gas. The density of the gas can then be determined from dielectric constant data.

The relation used is

$$K = (f_o/f)^2$$

where K is the relative dielectric constant, f_0 is the resonant frequency of the evacuated cavity, and f the resonant frequency of the cavity when filled with the dielectric.

B2. Attenuation Measurement

Changes in the attenuation constant of the microwave signal can be measured in the following way. Signals from a microwave oscillator are fed into a reference channel and a test channel. They are detected and compared. A variable attenuator is adjusted so that the magnitude of the detected reference signal is equal to the magnitude of the detected test signal, resulting in a null when the fluid is at a reference density. When a change in the density of the medium occurs, the amplitude of the detected test signal will change. The variable attenuator is used to renul the differential voltmeter and measure the change of attenuation.

This approach has not been extensively tested for static density measurements. It is being used in connection with the flow-rate measurements [72638].

B3. Phase Shift Measurement (Frequency Domain Reflectometry)

Changes in the phase constant of the microwave signal can be measured with the following way. Signals from a microwave oscillator are fed into a reference channel and a test channel. The test signal travels through the liquid and into a balanced mixer. The reference signal goes through a variable phase shifter and into the balanced mixer. The phase shifter is adjusted so that a differential voltmeter is nulled when the liquid is in its initial density state. When a change in the density of the liquid occurs, the phase angle of the test signal changes and the differential voltmeter will no longer be nulled. The phase shifter is used to restore the null and to measure the phase shift. The measured phase shift $\Delta\phi$ (degrees) is related to the change in the relative dielectric constant $\Delta\epsilon$ of the liquid as

$$\Delta\epsilon = (\lambda \epsilon / 180\ell) \Delta\phi$$

where λ is the free-space wavelength of the microwave signal, ϵ is the dielectric constant of the medium at its initial density, and ℓ is the distance between the microwave horns.

B4. Transmission Time Measurement

A microwave signal generator is swept in frequency over its spectrum. The sweep signal has a sawtooth or "ramp" waveform so that a linear frequency-versus-time output results from the microwave signal generator. The microwave signal travels from the generator to a mixer by two routes, one of which includes the space between the horns in the liquid. The instantaneous frequencies of the two signals fed into the mixer are designated f and f' , both of which vary linearly at the same rate with time.

The mixer is essentially a product demodulator, i.e., a device having an output signal that is the product of its input signals. The output spectrum contains frequency sums

and differences, but all except the difference frequency $(f - f')$ are filtered out. This difference is a function of the relative dielectric constant and hence the density of the fluid between the horns. The equation that relates changes in the relative dielectric constant to the difference frequency Δf is

$$\Delta \epsilon \approx \frac{2t_s \epsilon_0}{(f_2 - f_1)t_0} \Delta f$$

where t_s is the period of the sweep signal, ϵ_0 is the dielectric constant of the fluid, $(f_2 - f_1)$ is the sweep bandwidth of the microwave signal generator, and t_0 is the initial transmission time of the signal through the liquid.

C. Radiation Attenuation

C1. β or γ or infrared

The attenuation of incident radiation I_0 in passing through a thickness ℓ of a medium of density ρ is given by

$$I/I_0 = e^{-\mu \rho \ell}$$

where I is the transmitted radiation, and μ is an attenuation coefficient. Thus, for fixed source strength, materials, geometry, a signal which is dependent only on density should result. For oxygen a series expansion in terms of the attenuation ratio may have to be considered, since the attenuation curve for nitrogen has a small curvature [52723].

C2. Neutron Absorption

Very similar to C1 above, except that the radiation to be absorbed consist of thermal neutrons. He^3 is used to absorb the neutrons and is added in trace amounts to the pressurizing gas in the ullage volume. The density of the He^3 is monitored by measuring the attenuation of a neutron flux passing through a gap of fixed length located within the tank. Required are a thermal neutron source, two neutron detectors, and an absorption chamber.

For liquid level applications see also general discussion on page 33.

D. Buoyancy, Magnetic Plummet

The principle exploited is that of electro-magnetic suspension of a totally immersed plummet. Constructed of a ferrous alloy and/or a ceramic material coated with teflon, spherical in shape, this plummet is totally immersed in the liquid. Its position is sensed by a pair of search coils fed with a high frequency supply. These coils in conjunction with the plummet, act in a manner similar to a differential inductive displacement transducer. The plummet selected is of a slightly greater density than the maximum of the liquid, so that it is always tending to sink. It is prevented from sinking by electro-magnetic force from a

solenoid situated directly above it. The search coils allow just sufficient current to flow in the solenoid coil to maintain the plummet centrally between them in a liquid of given density.

D. Mechanical Float

See general discussion of page 35.

E. Acoustic

E1. Reflection

Utilizes the reflection of normally incident longitudinal acoustic wave pulses. At normal incidence the reflection coefficient for these planewaves depends only on the characteristic acoustic impedance of the adjacent media at the boundary. Since the liquid's characteristic impedance equals ρc where ρ is the density and c the velocity of sound, if the probe's impedance Z , is known, measurements of the reflection coefficient at the boundary, together with a measurement of the speed of sound in the medium enables one to determine the liquid density ρ .

E2. Magnetostrictive

Uses the acoustic damping difference between liquid and vapor to determine liquid level. A driving coil produces an oscillating magnetic field around a tubular magnetostrictive element. The element elongates and contracts at ultrasonic frequencies. A separate coil senses the element motion and provides a positive feedback signal to sustain circuit oscillation. When the element is restrained in the liquid the feedback signal is lost and oscillation stops. A detector circuit rectifies the oscillations to drive an output device.

E3. Piezoelectric

a. As density balance. A refrigerated quartz sensor crystal acts as a miniature condenser (cryopump) freezing out the gases arriving at its surface. The mass measurement is based on the linear response of such a device according to the relationship

$$\Delta f/\Delta t = C (\dot{m}/A_c) f_r^2 ,$$

where $\Delta f/\Delta t$ is the response of the crystal per unit time in Hz/sec, C is the crystal constant, \dot{m} is the rate of mass buildup on the crystal in g/sec, A_c is the crystal area in cm^2 , and f_r is the crystal's resonant frequency in Hz. Although the value of C in the equation is generally about 2.26×10^{-8} , a calibration is deemed necessary to more accurately determine the crystal's response.

b. As a liquid level device, see below.

For liquid level applications see also general discussion on page 37.

F. Forced Harmonic Oscillation

F1. Vibrating Cylinder - Transverse Mode

The mass of any vibrating system is a primary factor in determining the dynamic characteristics of the system. If the system is designed so that the fluid in it by damping affects the vibrating mass, a means of measuring fluid densities will have been provided. If a sinusoidal driver is used the result is a familiar classical equation for a vibrating system having one degree of freedom. A dynamometer can be used to measure the acceleration reaction, and an output voltage. If the output voltage is rectified the relation used is

$$\rho = a + b \cdot v$$

where ρ is the density, a and b are calibration constants and v is the d.c. voltage.

F2. Vibrating Cylinder - Hoop Mode

A thin cylinder is set in "circumferential" oscillation at its resonant frequency by an electromagnetic field. The frequency of oscillation is detected by a pick off coil. The fluid is allowed to surround both inside and outside the cylinder and therefore is also in oscillation. The resonant frequency depends upon the total mass of the oscillating system. Therefore, the fluid density will alter the frequency of oscillation. Resonant frequencies are measured for vacuum, liquids of known density and the samples. Accuracy in frequency measurement is achieved by comparison to a signal from a highly stable quartz crystal oscillator.

F3. Vibrating Reed

The reed is forced to move with a simple harmonic motion, causing an acceleration of the surrounding fluid. The vane oscillates at a resonant frequency determined by the density of the surrounding fluid. As the fluid density increases, the frequency of vibration decreases. Similarly, as the density decreases, the frequency of vibration increases in accordance with the following general relationship.

$$\text{Density} = \frac{A}{f^2} - \frac{B}{f} + C \text{ or } At^2 - Bt + C$$

where A , B , C are constants independent of the fluid,

f = frequency (cycles per second)

t = period = $\frac{1}{\text{frequency}}$ (seconds per cycle)

F4. Paddle Wheel or Paddle

At constant velocity and rotational speed the torque on a screw propeller is proportional to the density of the fluid in which it is immersed.

For liquid level applications see also general discussion on page 41.

G. Pressure

A great many liquid level sensing devices are based on pressure indications. A system of considerable utility and ruggedness is the widely used differential pressure gaging technique. Other devices are based on vapor pressure, on gas bubblers, on a bell sealed with mercury, and on the action of a diaphragm. A good source for discussion of pressure gaging devices is the survey article by Considine [49030], who mentions several additional devices such as the mercury U tube, bellows, and diaphragm force balance systems which apparently have not found applications in cryogenic service yet.

G1. Differential Pressure

Differential pressure gages use the simple relation $\Delta p = \rho h$, where Δp is the pressure differential, ρ the density, and h the height of the liquid. Vapor densities are ignored as being very small in comparison to the liquid. The gages measure the hydrostatic head of liquid in a vessel by means of two pressure taps — one connected to the ullage space above the liquid and the other to the bottom of the tank. If several sources of potential error are eliminated, the remaining inaccuracies of these systems are associated with gage imprecision and uncertainty of the actual fluid density at any given range of operating temperatures.

G2. Vapor Pressure

The principle used is that of a vapor pressure thermometer. A closed system is filled with the gas under consideration. A part of the closed system is brought into contact with the liquid. The gas inside the closed system condenses, the liquid level inside the closed system closely approaches that in the tank, and the pressure indication, that is the vapor pressure, is taken as a temperature indication. If the liquid level in the tank drops the gas in the closed system is free to evaporate with an accompanying change in pressure.

G3. Bubbler

Quite similar to the differential pressure above, except that one leg measuring the hydrostatic head is immersed in the cryogenic liquid and is purged by a flow of gas metered to give continuous moderate bubbling from the submerged end of the tube in the tank. Either liquid level or density can be indicated.

G4. Mercury Sealed Bell

Again quite similar to the ordinary differential pressure device, except that they are designed to work in vessels under pressure, and that a mercury column is used to transmit the hydrostatic head.

G5. Diaphragm Box

The element sensing the difference in pressure is a diaphragm.

H. Optical

See page 45.

I. Heat Transfer

Resistors exhibit a sharp rise, or a sharp fall in resistance when cooled to cryogenic temperatures. For example, carbon resistors and other semiconductors, i.e., transistors, thermistors, or diodes, have a larger resistance at low temperature, while electrical conductors such as metals and alloys normally show a drop in resistance. This effect alone would not distinguish between liquid and vapor, because at the interface they are at the same temperature. However, with current flowing every resistor dissipates power as heat. And, since the thermal conductivity of the liquid is much greater than that of the vapor heat transfer in the liquid is much faster than in the vapor. The temperature of a probe in liquid is, therefore, practically the same as the liquid temperature, while in the vapor the probe temperature is much hotter. Suitable detector circuitry is arranged to measure the resistance change caused by the change in probe temperature.

For liquid level applications see also general discussion on page 46.

J. Thermal Expansion

See page 50.

4. Survey of Instruments

For each instrument the description given follows a set format. Included in this format are reference(s), instrumentation type, physical principle, phase of operation, a description of the instrument, materials of construction significant to oxygen compatibility, calibration method, performance characteristics, oxygen service, and limitations.

Several of the items listed, specifically phase of operation, calibration method, and limitations, are included only if significant enough to warrant separate mention. For example, density calibrations are normally accomplished against "known" values of the saturated liquid where the actual conditions are established from equilibrium measurements of pressure and temperature. Similarly, liquid level devices are normally calibrated against visually measured heights.

Accuracy to the instrument manufacturer is always relative to the "known" values of the liquid. Seldom do instrumentation accuracies include an estimate of uncertainty for the primary or basic density data, which as we have seen is at least 0.1% under the best of circumstances.

A yes under oxygen service means that the device has been used for oxygen. Several devices have been marked yes for oxygen service because the references (patents) indicate

that they were designed for oxygen. All γ -ray devices have not been marked for oxygen service because actual oxygen experience could not be inferred, even though all of the apparatus is outside of the system to be measured, and compatibility problems would not be encountered.

The instruments are split into three sections, the first for density instrumentation, the second for specialized quantity gages for zero "g" applications, and the third for liquid level instrumentation.

4.1 Density Instruments

The order in which the instruments are presented follows the order of physical principles given in table 1. A list of the density instruments reviewed is presented in table 2, and a survey of the instrumentation by instrument type has been accomplished in table 3.

Table 2. List of Density Instruments

<u>A. Capacitance</u>	<u>E. Acoustic</u>
1 - Fluid Density Coaxial Capacitor	14 - Ultrasonic Mass Flowmeter
2 - Density Measurement Device	15 - Orbiting Density Instrument
3 - Two-Phase Capacitance Meter	<u>F. Forced Harmonic Oscillation</u>
4 - Liquid Level and Mass Systems	16 - Densitometer
<u>B. Microwave</u>	17 - Density and Specific Gravity Instrument
5 - Open-Ended Microwave Cavity	18 - Cryogenic Densitometer
6 - Liquid Storage Measuring System	19 - Supercritical Mass Sensor
7 - Microwave Densitometers	These items are described in section 4.2.
8 - RF Mode Analysis	
<u>C. Radiation Attenuation</u>	<u>Z. Quantity Gaging, Zero "g"</u>
9 - Local and Average Liquid Density	20 - Trace Injection of Radioactive Gas
10 - Beta-Ray Densitometer	21 - Trace Injection of Infrared Sensitive Gas
11 - Nuclear Densitometer	22 - Cryogenic Fuel Gage
12 - Gamma-Ray Densitometer	23 - Ullage Pressure Gage
<u>D. Buoyancy</u>	24 - Spherical Tank Gage
13 - Magnetic Densitometer	25 - Tank Level in Space

1. Fluid Density Coaxial Capacitor

Reference: [31982]

Instrumentation Type: density, static, also density, dynamic

Physical Principle: dielectric constant, capacitance

Phase of Operation: liquid, gas, liquid-gas two phase

Table 3. Density Instruments by Instrumentation Type

Instrument Type	Item Number in Section 4													
static density*	1	2	4	5	7	8	9	10	12	13	16	17	18	22
dynamic density	1	2	3	5	11	14	16	17	18					
low or zero "g" density*	8	18	20	21	22	23	24	25						
very low density	15													
supercritical density	4	6	8	19										

* Items 20-25 from section 4.2.

Description:

Densitometer is a series of concentric cylinders comprising a capacitor which is placed in the fluid to be measured. There are no moving parts, however, a flow straightener (venturi) is required. Item is similar to item 2, and item 3 below.

Materials of Construction: glass-metal seal, lead wires, insulation

Calibration Method: capacitor in vacuum, read out calibrated directly to density for each different material

Performance Characteristics: not given, dynamic, time constant "rapid?"

Oxygen Service: No

Other Fluids: H₂

2. Density Measurement Device

Reference: [57302, 31829]

Instrumentation Type: density, dynamic, also density, static

Physical Principle: dielectric constant, capacitance

Description:

A density measuring device capable of sensing the dielectric constant of a fluid or mixture and thereafter electronically computing density by rigorous solution of the Clausius-Mossotti equation. Capacitor uses coaxial cylindrical elements. Line capacitance can be compensated for. Manufacturer's information is found in [V1626]. Densitometer is normally coupled with a flow meter.

Performance Characteristics: not given

Oxygen Service: Yes

Other Fluids: H₂, N₂, He

3. Two-Phase Capacitance Meter

Reference: [61373]

Instrumentation Type: density, dynamic

Physical Principle: dielectric constant, capacitance

Phase of Operation: liquid-gas two phase

Description:

A three dimensional wire matrix capacitance was used as a density meter in 4" propellant feedline. Error analysis of this paper is unusually thorough. For example included is the temperature effect on the capacitor and the effect of slip, i.e., liquid and gas not travelling at the same velocity. A schematic of the system is shown in figure 1.

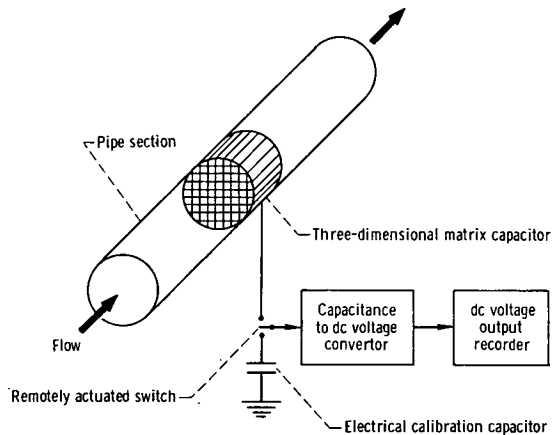


Figure 1. Schematic of the Two-Phase Capacitance Meter

Materials of Construction: stainless steel, lead wires, teflon insulation

Calibration Method: stray capacitance by reference to vacuum, and for temperature coefficient

Performance Characteristics:

static, accuracy $\pm 3\%$ for 100% liquid	dynamic, time constant depends on
max. 15% going from 100% gas	volume matrix, density and
to 100% liquid	flow rate

Oxygen Service: No

Other Fluids: H_2

Limitations: flow blockage 13% of pipe area

4. Liquid Level and Mass Systems

Reference: [V1620, 20382, 21013, 40167, 29478]

Instrumentation Type: density, static and supercritical, liquid level, continuous

Physical Principle: dielectric constant, capacitance

Description:

Concentric cylinders form the basis of the capacitance measurement see figure 2 from [40167]. With the cylinders vertical the capacitance yields liquid density if totally immersed, or liquid level if partially immersed. Stringing a sequence of cylinders together and inserting a liquid level detector between cylinders allows continuous liquid level measurement. Compensation

for tank shape, temperature, and minor contaminants is possible. Propellant flow rates of up to 25 in/sec can be handled. A gage of this description approximately 25" long was used for the life support system in Apollo [V1633]. It had an accuracy of $\pm 3\%$ full range. Similar gages were used in the Saturn S-IV stage [29478], and also in the Centaur [40167]. Manufacturers information is also found in [V1631], and [V1632].

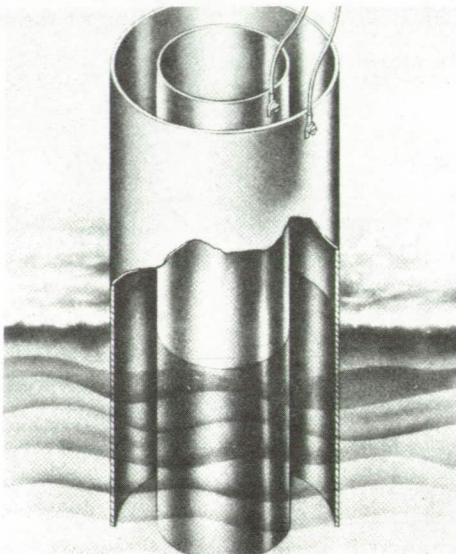


Figure 2. Typical Capacitance Gage, Concentric Cylinders

Materials of Construction: stainless steel, brass, aluminum teflon LOX
qualified for the S1C stage of Saturn V

Calibration Method: against a weighing system [29478]

Performance Characteristics:

static, accuracy $\pm 1\%$ full to $\pm 2\%$ empty

dynamic, time constant 280μ sec

response time 5 - 10 sec

liquid level resolution 0.1" in 588"

Oxygen Service: Yes

Other Fluids: H_2 , LNG, N_2O_4 ,
UDMH

Limitations: the gage has been used in zero "g" applications, however, capillary action of the fluid is troublesome, and gage tends to indicate "full" at all times.

5. Open-Ended Microwave Cavity

Reference: [40525]

Instrumentation Type: density, static and density, dynamic

Physical Principle: dielectric constant, microwave

Description:

An open ended cavity is used. Design curves are given which show the relation between the resonant frequency of the cavity and the cavity dimensions. The cavity consists of a circular waveguide that is terminated at each end with thin coaxial cylindrical partitions which are separated a certain distance. Microwave energy is supplied to the cavity through a small aperture in the side wall.

Materials of Construction: glass, silver plated brass

Calibration Method: static with saturation density from measurement of P and T, and a second cavity as reference cavity

Performance Characteristics:

static, accuracy .07%

Oxygen Service: No

Other Fluids: H₂

6. Liquid Storage Measuring System

Reference: [55656]

Instrumentation Type: density, supercritical

Physical Principle: dielectric constant, microwave

Description:

Very similar to item 5 except that the fluid container is used as the cavity. Spurious reflections from inside the cavity are avoided because the inside of the cavity is smooth and regular, and because conditions are restricted to supercritical states, i.e., no liquid-vapor interface.

Materials of Construction: lead wire, glass ceramic or teflon

Performance Characteristics: not given

Oxygen Service: No

Other Fluids: H₂

7. Microwave Densitometers

Reference: [72638]

Instrumentation Type: density, static

Physical Principle: dielectric constant, microwave

Description:

An as yet experimental instrument system. Three density instrumentation techniques were examined. All require that a microwave signal be propagated through a column of liquid. If done vertically, since all of the fluid in the column influences the microwave signal, the sample is representative of the fluid at all levels within the apparatus, i.e., no compensation for stratification is required. Two microwave horns are used and the electronics are altered to give either attenuation, phase-shift measurement, or transmission

time measurements. As used the methods measure differences from an initial state of saturated liquid density.

Materials of Construction: teflon

Calibration Method: liquid of known density

Performance Characteristics: improvements in accuracy are likely static, accuracy 0.5% est.

Oxygen Service: No

Other Fluids: N_2 , H_2

Limitations: signal interference in the form of spurious reflections need to be overcome.

8. RF Mode Analysis

Reference: [59402, V1629, V1634]

Instrumentation Type: density, static, density, zero "g"

Physical Principle: dielectric constant, microwave

Phase of Operation: liquid, gas, two-phase, zero "g", supercritical

Description:

Microwave energy is introduced into a tank so as to illuminate it by setting up electromagnetic fields throughout the entire volume of the tank. The tank interior is a dielectric region completely surrounded by conducting walls. Such a system is called a cavity, and the resonant solutions are the normal theoretical modes of the cavity. Figure 3 shows the RF system in block diagram form.

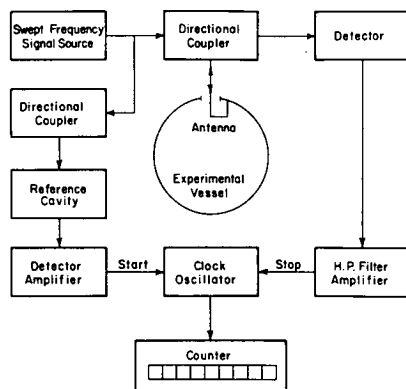


Figure 3. Block Diagram of RF Mode Analysis

The system is quite similar to item 7 above, the RF frequencies used are slightly lower than those in the microwave region. Considerable development work has been done very recently on both uniform density fluids, and non-uniform density fluids [V1634]. Linear readout now has 2.45% maximum deviation, while quadratic interpolation of the results yields less than 1% error for the fluids tested.

Materials of Construction: lead wires, teflon, crystal diode

Performance Characteristics:

static, accuracy 2.5% linear

response time 30 ms

Oxygen Service: No

Other Fluids: H_2 , N_2

9. Local and Average Liquid Density

Reference: [45921], probes are quite similar to item 10, below

Instrumentation Type: density, static

Physical Principle: radiation attenuation, β

Description:

The average bulk density of a liquid in a tank is indicated by a summation of a plurality of radiation density probes located at various points throughout the tank. Each probe contains a β -ray source and a solid state detector. Output is electrical current converted to density by pulse circuit techniques or current integrating techniques. Each probe provides an output signal of the local density. Apparatus is apparently particularly useful if large density gradients occur in the tank. Probes can be mounted on the tank walls.

Materials of Construction: teflon resin, stainless steel and silver solder - or epoxy

Calibration Method: not given

Performance Characteristics:

static, accuracy 1%

Oxygen Service: Yes

Other Fluids: H_2

10. Beta-Ray Densimeter

Reference: [67109], oxygen service inferred from item 9 above

Instrumentation Type: density static

Physical Principle: radiation attenuation, β

Description:

A source of β -radiation is placed at a suitable fixed distance from a detector with liquid between source and detector. Pulses are counted directly, or can be converted to a d.c. signal proportional to the pulse rate. Uncertainty estimate is based on the statistical scatter of the count rates with a $\pm 2 \sigma$ error band, i.e., 95% confidence for liquid hydrogen.

Materials of Construction: stainless steel

Calibration Method: liquid of known density

Performance Characteristics:

static, accuracy 1%

Oxygen Service: Yes

Other Fluids: H_2

Limitations: complex associated electronics

11. Nuclear Densimeter

Reference: [52723]

Instrumentation Type: density, dynamic

Physical Principle: radiation attenuation, γ

Phase of Operation: liquid-gas two phase

Description:

Gauge consists of 1/2 curie Co^{60} γ -ray source, liquid scintillator with a photomultiplier tube detector. The gauge is not in the flow stream, therefore temperature compensation or oxygen compatibility problems are avoided.

Materials of Construction: not applicable

Calibration Method: static tests with many tubes each of which could be individually purged resulting in void fractions up to 70%

Performance Characteristics:

static, accuracy: quality to within 5-10 quality percent dynamic, time constant 5-10 millisecc

Oxygen Service: No

Other Fluids: N_2 , H_2

Limitations: radiation hazard

The flowing quality will be equal to the thermodynamic equilibrium quality only if liquid and gas are moving at the same velocity.

12. Gamma-Ray Densimeter

Reference: [67109, 56204, 45221, V1630]

Instrumentation Type: density, static

Physical Principle: radiation attenuation, γ

Description:

Sources and detectors were mounted externally on opposite sides of the tank.

The beam penetrates the walls of the tank as well as the fluid.

Materials of Construction: not applicable

Performance Characteristics:

static, accuracy 0.5%

Oxygen Service: No

Other Fluids: H_2

Limitations: radiation hazard

13. Magnetic Densimeter

Reference: [V1622], see also [72829]

Instrumentation Type: density, static

Physical Principle: buoyancy, magnetic plummet

Description:

Instrument operates on the principle of electromagnetic suspension of a totally immersed plummet. The feature which leads to high accuracy is that the instrument is basically measuring only the difference in liquid and plummet densities, referred to as the p.d.d. (plummet density difference).

Consequently the best results are obtained when liquid density is close to plummet density. Instrument performance will deteriorate as this density difference increases. Basic accuracy of the instrument is better than 0.1% p.d.d., under controlled conditions of temperature.

Materials of Construction: ferrous alloy, gold, stainless steel, epoxy resin, teflon

Calibration Method: various liquids of known density to cover the instrument range

Performance Characteristics:

static, precision 0.1% of p.d.d.

accuracy of calibration $\pm 0.0001 \text{ g/cm}^3$

Oxygen Service: No

Other Fluids: N_2 , H_2

14. Ultrasonic Mass Flowmeter

Reference: [V1619]

Instrumentation Type: density, dynamic

Physical Principle: acoustic, reflection

Description:

A fuel flowmeter consisting of a flow velocity meter, a densitometer, time intervalometer. The densitometer consists of a stepped diameter probe; the difference in echo amplitudes at the wetted end and at the dry step is a function of the acoustic impedance ρC of the fuel, where ρ is the fuel density. The time intervalometer measures the time τ between two successive echoes which is proportional to $1/C$. No rotating parts, no intruding parts, flow stream is square channel, will need flow straighteners.

Materials of Construction: quartz crystal lead wires

Calibration Method: calibration would probably be of the whole unit, i.e., a flowmeter type calibration and should be against new velocity of sound data [86304].

Performance Characteristics: estimates that 1% in mass flow rate is possible

static, accuracy $\pm 2\%$ est.

, dynamic, time constant 20 ms

Oxygen Service: No

Other Fluids: Jet fuel

Limitations: two-phase flow not explored

15. Orbiting Density Instrument

Reference: [54525, 69782]

Instrumentation Type: density, very low

Physical Principle: acoustic, piezoelectric

Phase of Operation: free molecular gas

Description:

A piezoelectric crystal is used as a micro balance. The crystal is cooled to very low temperatures and acts as a cryopumping gas collector. The gas has to be at very low density, i.e., similar to air densities at altitudes of 140 to 280 km. Measurement is made through the beat frequency between the crystal and a variable oscillator.

Materials of Construction: quartz, aluminum, lead wires

Calibration Method: against McLeod gage see [69782]

Performance Characteristics: linear for pressures from 2×10^{-6} to 6×10^{-4} Torr
with sensitivity of 1.703×10^8 Hz/g
static, accuracy 6% for the continuous collection mode

Oxygen Service: air

16. Densitometer

Reference: [15361, 42209]

Instrumentation Type: density, dynamic, also density static

Physical Principle: forced harmonic oscillation, vibrating cylinder

Phase of Operation: liquid, liquid-gas two phase

Description:

The instrument uses a movable section of flow passage, vibrated transversely at a constant amplitude and frequency, as the sensing element. A dynamometer inserted between the flow passage and driver continuously measures the acceleration reaction, that is the product of mass and acceleration.

Allowable flow velocity up to 7 fps for which densitometer is insensitive to drag or momentum effects.

Materials of Construction: beryllium copper, 316 stainless steel

Calibration Method: vs. static density of known fluid

zero shift for room temperature vs. $\text{LO}_2 \sim 5\%$

Performance Characteristics:

static, accuracy $\pm 2\%$

Oxygen Service: Yes

Other Fluids: H_2 , N_2 , water

17. Density and Specific Gravity Instrument

Reference: [V1623, V1624]

Instrumentation Type: density, dynamic also density, static

Physical Principle: forced harmonic oscillation, vibrating cylinder

Description:

A thin cylinder "spool" is set into "circumferential" oscillation at its resonant frequency by an electromagnetic field. With fluid surrounding the inside and outside of the spool, see figure 4, the resonant frequency depends on the total mass of the system. This frequency is measured by a pick-off coil and converted into measured times. The meter transmits a pulse frequency signal according to: $d = d_o [(T/T_o)^2 - 1]$ where

d = measured density g/l

d_o = meter constant g/l

T = periodic time at density d , micro-seconds, and

periodic time = $\frac{1}{\text{frequency}}$

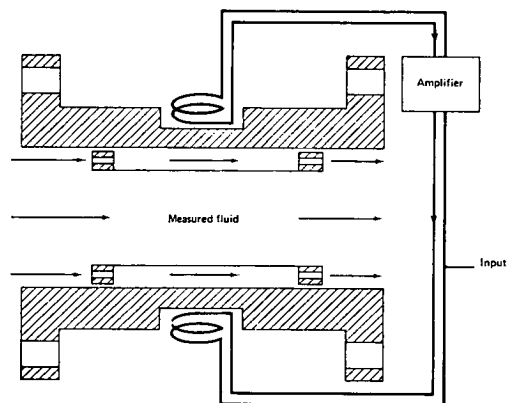


Figure 4. Density Instrument Using Hoop Mode Vibration

A temperature reference circuit is utilized to allow the density signal to be referred to a particular temperature for specific gravity computation. The densitometer described in [V1624] is very similar to [V1623], except that it is used almost exclusively on natural gas

Materials of Construction: 316 stainless steel, spool can be gold or silver plated

Calibration Method: against vacuum and liquids of known density

Performance Characteristics:

static, precision 0.01%

dynamic, time constant 1 millisec

accuracy liquids $\pm 0.1\%$ of range ± 0.5 g/l

gases $\pm 0.1\%$ of range ± 0.005 g/l

Oxygen Service: Yes

Other Fluids: H_2 , N_2 , He, natural gas

Limitations: viscosity effects possible above 20 centipoises but can be adjusted for by mode of installation

18. Cryogenic Densitometer

Reference: [V1621]

Instrumentation Type: density, dynamic, also density static

Physical Principle: forced harmonic oscillation, vibrating reed

Phase of Operation: includes low or zero "g"

Description:

A sensing vane is positioned across a supporting cylinder. The vane is driven to move in simple harmonic motion causing an acceleration of the surrounding fluid. The resonant frequency is measured. It is related to density in a three term power series. The densitometer can be used with a number of volume flow measuring devices, such as turbine type flowmeters, orifice plates, flow nozzles, etc., to determine mass flow rates for engine control and propellant quantity gaging. Combined with tank gauges, the mass contents of the tanks can be determined. When used with turbine or positive displacement meters, fluid custody transfer on a mass basis is possible. Additional information on theory of operation is available in [V1625].

Materials of Construction: 316 stainless steel and monel

Calibration Method: against vacuum and materials of known density

Performance Characteristics: not given

Oxygen Service: No

Other Fluids: H_2 , N_2 , hydrocarbons, water

Limitations: maximum liquid viscosity 100 centipoises

19. Supercritical Mass Sensor

Reference: [63791]

Instrumentation Type: density, supercritical

Physical Principle: forced harmonic oscillation, paddle wheel

Phase of Operation: supercritical

Description:

A screw propeller is run at constant rotational speed with fluid flowing at constant velocity past the propeller. Flow is directed with flow straighteners. Torque on the assembly is measured with a rotatable magnetic core. Apparatus is designed for space applications. Tank volume has to be known to obtain the mass.

Materials of Construction: not given

Calibration Method: similar to turbine flow meter

Performance Characteristics: not given

Oxygen Service: No

Other Fluids: probably H_2

4.2 Specialized Quantity Gages for Zero "g"

Several gaging systems specifically designed for zero "g" applications are listed below because the variable actually measured is volume, or because the physical principle used is unique to the particular application, and is, therefore, not easily integrated with the entries in table 1.

20. Trace Injection of Radioactive Gas

Reference: [54388]

Instrumentation Type: quantity gaging, zero "g"

Physical Principle: radiation attenuation, β and γ

Description:

This system is very similar to items 21 and 22, except that the trace gas injected is radioactive. Krypton-85 is injected into the ullage space and the tank is pressurized. As the propellant is consumed, the ullage space volume increases and the volume concentration of the radioactive gas is decreased. This "dilution" of the gas is continuously measured, and the measured count rate, being proportional to the krypton-85 concentration, is related to the propellant remaining by a simple algebraic equation. To insure homogeneity the gases are mixed by a circulation fan.

Materials of Construction: bladder, tank

Performance Characteristics:

static precision: 0.3% of tank volume at a level of 1 σ

counting time: 10 sec, average lag time 5 sec which is equivalent to 0.4% at the outflow rates used

Oxygen Service: Yes

Other Fluids: H_2

Limitations: Requires bladder to contain liquid, pressurizing gas, and a mixer.

21. Trace Injection of Infrared Sensitive Gas

Reference: [49055]

Instrumentation Type: quantity gaging, zero "g"

Physical Principle: radiation attenuation, infrared

Description:

This system is very nearly identical to item 20 above, except that the trace gas injected absorbs strongly in the infrared. A measured quantity of trace gas is injected into the ullage space where it mixes with the pressurizing gas.

The change in total gas mixture density is detected by the change in infrared absorption. A schematic of the system is shown in figure 5 below.

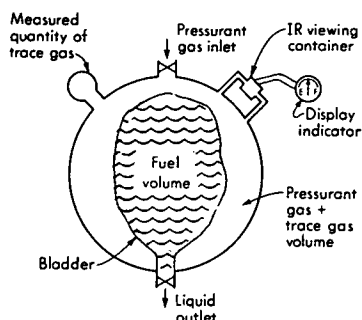


Figure 5. Schematic of System Using a Trace Gas

Materials of Construction: bladder, tank

Calibration Method: second cell with reference mixture

Performance Characteristics: not given

Oxygen Service: No

Other Fluids: H_2

Limitations: Requires bladder to contain liquid, pressurizing gas, and a mixer

22. Cryogenic Fuel Gage

Reference: [63792, 69782]

Instrumentation Type: quantity gaging, zero "g", density static

Physical Principle: radiation attenuation, neutron absorption

Description:

This fuel gaging system measures the quantity of cryogenic propellant in a tank utilizing a trace material of Helium³ in the pressurizing gas normally associated with the propellant in a closed tank. Actually measured is the ullage volume. This volume is subtracted from total tank volume giving liquid volume. Liquid volume is converted to liquid mass based on the temperature of the liquid. System requires a vortex generator, described in [55680], to create a vapor bubble or ullage space for zero or low gravity conditions. Also requires a measurement of temperature.

Materials of Construction: not given

Calibration Method: in flight recalibration possible by additional He³ injection

Performance Characteristics: will depend on the length of counting

accuracy estimated to be similar to other radiation absorption devices

Oxygen Service: No

Other Fluids: H_2 , F_2

23. Ullage Pressure Gage

Reference: [49055, 55657, V1628]

Instrumentation Type: quantity gaging, zero "g"

Physical Principle: acoustic - gas compressibility

Description:

This gas compressibility system derives the liquid volume from pressure changes in the ullage volume, and the known volume of the tank. A small reciprocating piston produces a continuous known change in the ullage. A second piston operates in a similar manner in a small reference chamber which communicates with the main tank. The pistons are in the form of low frequency loud speakers with flexible diaphragms. The second piston is driven so that the pressure variations in the two volumes are made equal. The reference piston stroke is measured and related to the ullage volume. The schematic shown in figure 6 below and the performance parameters were taken from [V1637].

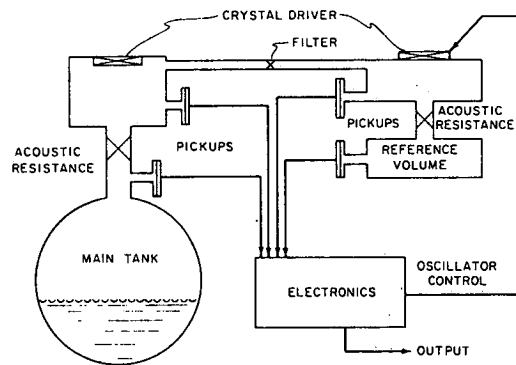


Figure 6. Schematic of an Acoustic Ullage Sensor System

Materials of Construction: sylphon a plastic, stainless steel

Performance Characteristics:

static, accuracy $\pm 1\%$ full to $\pm 2\%$ empty

response time 5 - 10 seconds

Oxygen Service: No

Other Fluids: H_2

24. Spherical Tank Gage

Reference: [74581]

Instrumentation Type: quantity gaging, zero "g"

Physical Principle: mechanical dipstick

Description:

Inside a spherical tank a flexible bladder contains the liquid. The bladder is preloaded to form the liquid into a predictable shape under zero gravity conditions. As liquid is expelled the bladder collapses and drives a flexible wire, the dipstick, past a reference point. Liquid quantity is measured from the position of the bladder. A temperature measurement is probably also necessary.

Materials of Construction: not given, mylar

Performance Characteristics:

static, accuracy $\pm 5\%$

Oxygen Service: No

Other Fluids: H_2

25. Tank Level in Space

Reference: [34218]

Instrumentation Type: quantity, low "g"

Physical Principle: acceleration in orbit

Description:

Tank level in space can be measured by applying a known impulse and measuring the resulting acceleration of the container. From this the mass of the container plus remaining liquid can be calculated. Two cases are possible. Continuous thrust until all of the liquid has settled into one end, when conventional sensors can be used. In this method the mass of the remaining liquid can be found from Newton's second law. In the second case a single thrust impulse is used and the tank acceleration is monitored continuously until a steady state is reached. In this case a slightly different form of Newton's second law is used, the integral of the acceleration being used to obtain the total velocity change of the system.

Materials of Construction: not applicable

Performance Characteristics: not given

Oxygen Service: No

Other Fluids: H_2

4.3 Liquid Level Instruments

A comprehensive survey of liquid level instrumentation for processes in chemical engineering has been published by Considine [49030]. While this article is not directed specifically towards cryogenics it is quite valuable because it gives characteristics, illustrations, advantages and disadvantages and suppliers of industrial measurement systems. For cryogenic applications the test results on point sensors for hydrogen conducted by the National Bureau of Standards for NASA [16980] are most comprehensive.

The order in which the instruments are presented again follows the order of physical principles given in table 1. Quite often a number of references accumulate for a given physical principle, and we give an overview for the technique under the heading of general discussion. If a number of papers refer to the same or very similar devices, then the description given is a composite of all the papers, extracting the pertinent facets from each one. A list of the liquid level instrumentation reviewed is presented in table 4. A survey table similar to table 3 is not very informative because there are only two major categories of instruments, point sensors and continuous sensors, and, as pointed out earlier, the distinction between the categories is not all that clear-cut.

A. Liquid Level with Capacitance

General Discussion: Since the dielectric constant of the liquid phase is appreciably different from that of the vapor phase, a level sensor consisting for example of two vertical plates or concentric cylinders can be used to detect differences in total fluid capacitance resulting from variations in liquid level. Continuous measurement is accomplished with a long probe running from top to bottom of the inner shell, whereas point indications can be obtained with capacitance ring devices which simply sense and differentiate between fluid phase capacitances (liquid vs vapor) and indicate which phase the sensor sees, as shown in figure 7.

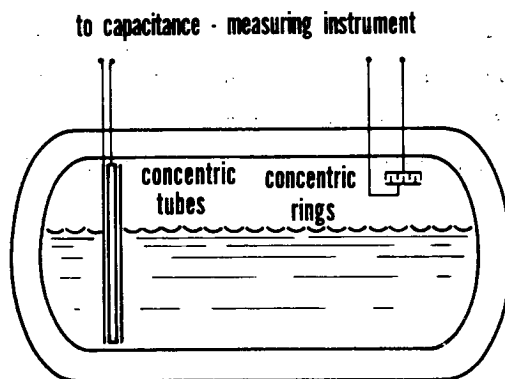


Figure 7. Liquid Level with Capacitance

Table 4. List of Liquid Level Instruments

<u>A. Capacitance</u>	<u>F. Forced Harmonic Oscillation</u>
26 - Bullseye Capacitor	43 - Vibrating Paddle
27 - Bullseye - Continuous	<u>G. Pressure</u>
28 - Ceramic	44 - Differential Pressure
29 - Concentric Cylinders Continuous	45 - Vapor Pressure
<u>B. Microwave</u>	46 - Gas Bubbler
30 - Microwave Cavity	47 - Mercury Sealed Bell
31 - Phase Shift Detector	48 - Diaphragm Devices
32 - Time Domain Reflectometer	<u>H. Optical</u>
<u>C. Radiation Attenuation</u>	49 - Optical Point Level Sensor
33 - Collimated γ Beam	<u>I. Heat Transfer</u>
34 - Motor Driven Level Gage	50 - Hot Wire Devices
35 - Level Control for LOX Trucks	51 - Wire Grid Sensor System
<u>D. Mechanical Float</u>	52 - Thermocouple Devices
36 - Vertical Static Float	53 - Semiconductor Devices
37 - Float Magnetically Sensed	<u>J. Thermal Expansion</u>
<u>E. Acoustic</u>	54 - Differential Thermal Expansion
38 - Thermal Oscillations	
39 - Soundwave in the Gas Phase	
40 - Ultrasonic Sensor System	
41 - Soundwave in the Liquid Phase	
42 - Piezoelectric Transducer	

A discussion of the diverse ways in which capacitance sensors can be applied is given in [48423]. To overcome the problem of large amounts of gas evolving in cooldown, porous sintered material is used [27087]. To provide compensation for tank shape the center electrode in the concentric cylinder arrangement can be profiled [75424].

26. Bullseye Capacitor

Reference: [16980]

Instrumentation Type: liquid level, point

Physical Principle: dielectric constant, capacitance

Description:

A set of concentric rings, alternately connected to the two leads, as shown in figure 8 below taken from [40167].

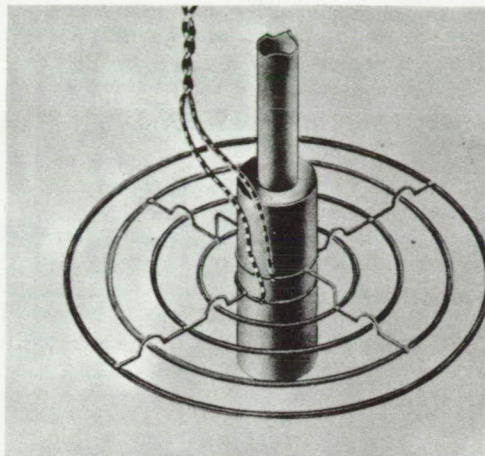


Figure 8. Capacitance Point Level Indicator

Materials of Construction: brass, stainless steel, teflon, lead wires

Performance Characteristics:

liquid level resolution: .1"

response time: 0.6 sec

Oxygen Service: Yes

Other Fluids: H_2 , N_2 , H_2O

Limitations: If the unit is not shielded positioning and capacitance of leads has to be considered. Newer models have a 3 terminal system and lead capacitance does not have to be considered.

27. Bullseye - Continuous

Reference: [49055]

Instrumentation Type: liquid level, continuous

Physical Principle: dielectric constant, capacitance

Description:

Very similar to item 4. A sequence of concentric cylinders with Bullseyes, item 26, used as liquid level detectors between cylinders.

Materials of Construction: brass, stainless steel, teflon, lead wires

Performance Characteristics:

liquid level resolution: 0.1"

Oxygen Service: Yes

Other Fluids: jet fuel

28. Ceramic

Reference: [77654]

Instrumentation Type: liquid level, point

Physical Principle: dielectric constant, capacitance

Description:

Sensor is a factory ceramic capacitor having a large temperature coefficient of capacitance.

Materials of Construction: ceramic, lead wires

Performance Characteristics:

liquid level resolution: 2 mm

Oxygen Service: No

Other Fluids: N₂

29. Concentric Cylinders Continuous

See item 4 under density instruments in section 4.1.

B. Liquid Level with Microwave

30. Microwave Cavity

The system described in item 5 could be used as a point sensor for liquid level, see reference [72638], however, an evaluation has not been conducted.

31. Phase Shift Detector

Reference: [73600]

Instrumentation Type: liquid level, continuous

Physical Principle: dielectric constant, microwave

Description:

A signal reflection method very similar to item 32. However, this method does not require a transmission line. Instrument is still in the development stage. Resolution given below can be improved considerably.

Materials of Construction: brass, stainless steel, teflon

Performance Characteristics:

liquid level resolution: 1%

Oxygen Service: No

Other Fluids: H₂

Limitations: subject to spurious reflections or distortions from surfaces or objects inside the dewar

32. Time Domain Reflectometer

Reference: [73600]

Instrumentation Type: liquid level, continuous

Physical Principle: dielectric constant, microwave

Description:

A pulse-echo method. A step generator launches a voltage step down the transmission line. The incident wave is reflected at the discontinuity, i. e., the liquid vapor interface. A standing wave is set up in the transmission line at the liquid gas interface and the transmission time measured, from which the distance is obtained. System is still experimental.

Materials of Construction: brass, stainless steel

Performance Characteristics:

liquid level resolution: 0.5% of span

response time: 20 msec

Oxygen Service: No

Other Fluids: H₂

C. Liquid Level with Nuclear Radiation

General Discussion: Several of the most common arrangements are shown in figure 9, which is taken from a good review paper [42111] on nuclear gaging techniques. Usually a gamma source is located at one side of a vessel and the radiation detectors on the other side. Since the radiation is absorbed by the liquid, only slightly absorbed the metal walls, and negligibly by the vapor, a reasonable indication of level is given by the detector readout. Other systems use a nearly collimated beam of γ rays, or injections of tracer gas into the ullage space.

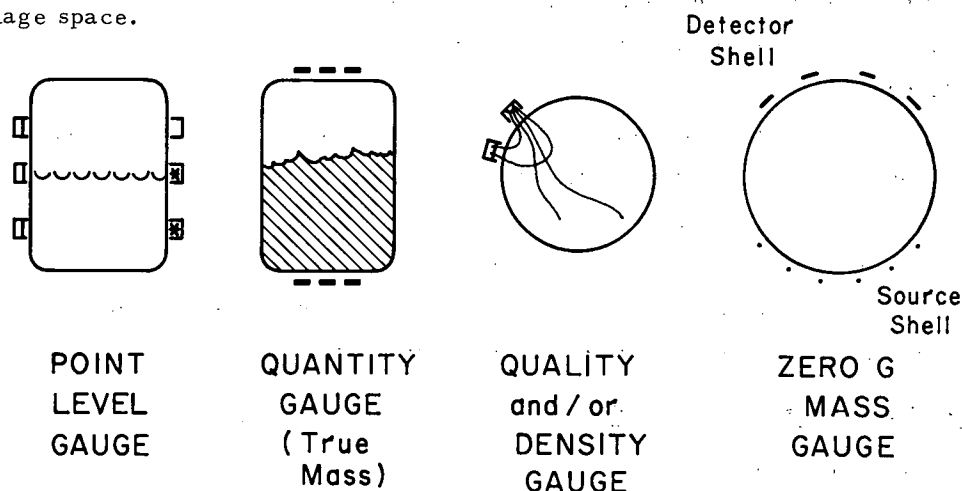


Figure 9. Cryogenic Applications of Nuclear Gaging

33. Collimated γ Beam

Reference: [25698, 64541]

Instrumentation Type: liquid level, point

Physical Principle: radiation attenuation, γ

Description:

Radiation source holder and scintillation detector were mounted outside of the LOX tank on an atlas missile. System was used for fill height indication.

Sufficient tests were run to give numbers for statistics to be applied to the liquid level data, i.e., 2σ is $\pm 1''$. Controlled tests were conducted to determine the effects of boiling and turbulence. Said effects can be cancelled out by proper calibration.

Note: The more recent use of a non-collimated beam from an Am 241 source with an accuracy of $\pm 2\%$ is described in [64541].

Materials of Construction: not applicable, not given

Calibration Method: against a hot wire type point sensor

Performance Characteristics:

liquid level resolution: $\pm 1''$ w/o calibration 0.1" with calibration
response time: 0.3 sec

Oxygen Service: Yes

Other Fluids: H_2 , pentaborane

Limitations: radiation hazard, complex electronics

34. Motor Driven Level Gage

Reference: [35565]

Instrumentation Type: liquid level, continuous

Physical Principle: radiation attenuation, γ

Description:

Very similar to item 33 above, with the addition of a frame and a motor drive.

Materials of Construction: not applicable, not given

Performance Characteristics:

liquid level resolution: $\pm 1/8''$ in 50"

Oxygen Service: No

Other Fluids: chlorine

Limitations: radiation hazard, complex electronics

35. Level Control for LOX Trucks

Reference: [42111]

Instrumentation Type: liquid level, point

Physical Principle: radiation attenuation, γ

Description:

Very similar to item 33 above. The gage was built for LOX and LN_2 cryogenic trucks. The previous filling procedure used a pressure sensor gage accurate to about 10%. The truck had to be weighed, and if overloaded, some of the fluid had to be dumped. The radiation dose rates from the source in this system are quite small: the measured dose rates with a standard survey meter are 2 mr/hr. at 16 inches from the source and 0 (unmeasurable) in the driver's seat. Figure 10 which describes this gaging arrangement has been taken from [70607].

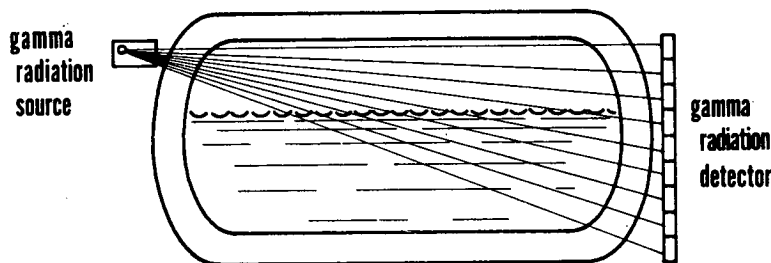


Figure 10. Nuclear Gaging of Truck Tanks

Materials of Construction: not applicable, not given

Performance Characteristics:

fill level cut-off repeatability was 0.7%

Oxygen Service: Yes

Other Fluids: N_2

D. Liquid Level by Float

General Discussion: "The simplest means of determining liquid level involves a float on the surface of the liquid. In one application of this method, a lightweight rod is fastened to the top of a slightly buoyant material, and its position is noted visually through a sealed glass column above the fluid space. A variation replaces the vertical indicator with a tape or cable that is used to move a digital readout external to the vessel. In another variation one or several magnet-bearing floats can be used to ride up and down a vertical tube, with magnetically actuated reed switches positioned at specific locations for point level indication [70607]." These three means are illustrated schematically in figure 11. Gages can be made oxygen compatible by encasing the float in thin stainless steel [32711]. Additional float devices such as a torque tube, and floats using mercury have been discussed by Considine [49030], however these devices have not yet found application in cryogenic service.

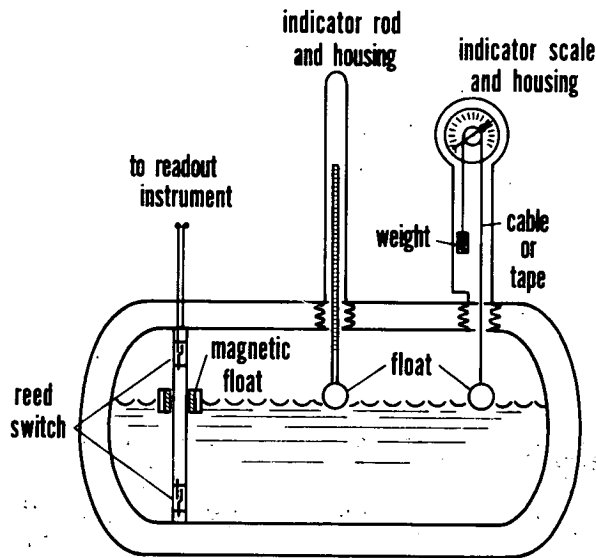


Figure 11. Liquid Level Schemes for Float Devices

Limitations: A relatively fragile, and sometimes poorly positioned glass housing for visual readout is required in some cases. A sealed conduit to the outside is required between the inner and outer tank wall. The floats are lightweight, and therefore subject to "hanging-up" or sticking. The instruments are very sensitive to liquid motion.

36. Vertical Static Float

Reference: [43449]

Instrumentation Type: liquid level, continuous

Physical Principle: mechanical float

Description:

A static float is housed inside of a guide tube which is welded to the tank wall. The float is held in the guide tube by means of isolating bellows at the top and bottom. A force transducer is mounted above and in contact with the upper bellows. The level of the liquid in the tank is proportional to the buoyant force acting on the float, which is transmitted to the transducer, yielding an output signal proportional to the liquid level.

Materials of Construction: copper, beryllium copper, stainless steel

Performance Characteristics:

liquid level resolution: typically $\pm 1-3\%$

Oxygen Service: No

Other Fluids: not given

37. Float Magnetically Sensed

Reference: [75380]

Instrumentation Type: liquid level, continuous

Physical Principle: mechanical float, magnetically sensed

Description:

Reference is chosen to illustrate that the magnetic type floats exist. Another reference [71127] demonstrates the use of a magnet for sensing and the use of a reed switch as fail-safe switch.

Materials of Construction: not given^{*}

Performance Characteristics:

liquid level resolution: typically $\pm 1/8''$

Oxygen Service: Yes^{*}

Other Fluids: N₂

E. Acoustic Liquid Level Gages

General Discussion: A large variety of liquid level gages use the acoustic principle. They differ in the way in which the soundwaves are generated. Thermal oscillations, or the sounds of boiling when a warm solid is brought into contact with the liquid surface is the simplest method. Electromechanical, magnetostrictive, and piezoelectric transducers are the more conventional methods. In addition, either gas or liquid can be used as transmitting medium. For example, the use of the liquid as medium is shown in figure 12, and is described in [70607] as follows: a transmitter feeds an electric pulse to a transducer where it is converted to an acoustic pulse travelling at sonic velocity to the liquid-vapor interface, reflected back at the same speed to the transducer, where it is reconverted to an electric pulse, and finally sent to a receiver. Knowing the velocity of sound in a given liquid, the pulse transit time from transmitter-to-interface-to-receiver becomes an indication of liquid level. In order to eliminate extraneous interfaces that may be caused by vapor bubbles in the liquid, a tubular stillwell often is used in the manner shown to isolate the measured fluid column from such physical disturbances. Bubbles also may be suppressed by slight pressurization - e.g., momentary closing of the vent valve - of the vessel immediately prior to any measurement. Typical liquid level resolution of these instruments is $\pm 0.5\%$ of span, and a response time of about 20 ms [49030].

^{*} These instruments are available in oxygen compatible units requiring only penetration of the tank walls for instrument wires [70607].

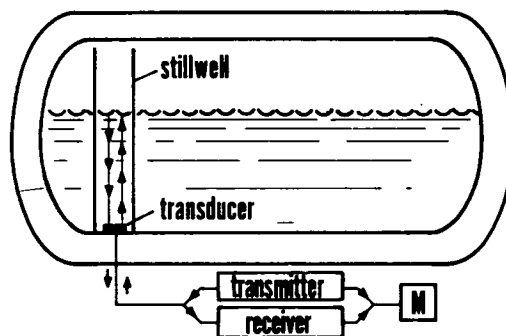


Figure 12. Acoustic Liquid Level Gage, Liquid Medium

Soundwaves in the gas using wires [34161] or a wire wound helix [34161, 67053] as acoustic wave guides have also been used for liquid level detection. A review of the design parameters affecting magnetostrictive liquid level sensors has been given by Ryder [43542]. Sensor performance is taken from [16980, 40123, and 49030].

38. Thermal Oscillations

Reference: [14264, 79310]

Instrumentation Type: liquid level, point

Physical Principle: acoustic

Description:

These devices are very simple liquid level detectors. They utilize the sounds of boiling, when a warm solid is brought into contact with a low temperature liquid surface. Ordinarily the technique is applied to liquid helium, see for example [79310]; it has, however, also been applied to nitrogen. A membrane, a stethoscope, or a diaphragm with electronic circuits can be used to detect the sound.

Materials of Construction: bronze, brass, copper, stainless steel

Performance Characteristics:

liquid level resolution: est. $\pm 1/4''$

response time: est. 0.5 sec

Oxygen Service: No

Other Fluids: He, N₂

39. Soundwave in the Gas Phase

Reference: [67053]

Instrumentation Type: liquid level, point

Physical Principle: acoustic, reflection

Description:

The electric pulse advancing in the transmission line is reflected from the point where the line impedance changes abruptly, i. e., at the point where the fluid is introduced into the line. A wire wound as a helix is used as the transmission line instead of the usual coaxial cable, effectively increasing the line length. The general scheme is shown in figure 13 below.

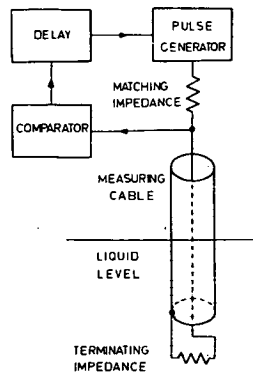


Figure 13. Acoustic Liquid Level Gage, Gaseous Medium

Materials of Construction: copper, perspex plastic

Performance Characteristics:

liquid level resolution: 0.5% of total span

response time: 20 millisec

Oxygen Service: No

Other Fluids: water, oil

Limitations: sensors are sensitive to cable length

40. Ultrasonic Sensor System

Reference: [16822, V1628]

Instrumentation Type: liquid level, continuous

Physical Principle: acoustic, piezoelectric

Description:

The system operates on the principle of continuous ultrasonic echo-sounding. It consists of a piezoelectric crystal transducer, stillwell assembly and an electronics package. Liquid level is gaged by measuring the time required for an ultrasonic pulse to travel from the transducer to the liquid surface and back again to the common transmit-receive transducer, as shown in figure 14 below.

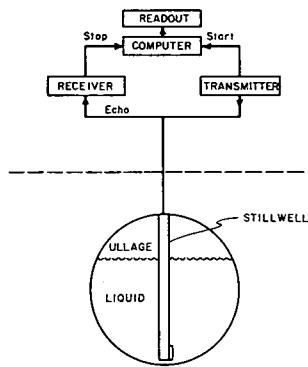


Figure 14. Ultrasonic Sensor System

Materials of Construction: quartz, bariumtitanate, stainless steel, epoxy

Performance Characteristics:

liquid level resolution: $\pm 0.5''$

response time: 25 msec

Oxygen Service: Yes

Other Fluids: H_2 , N_2 , H_2O , JP-4
fuel, oils

41. Soundwave in the Liquid Phase

Reference: [74852, 31962, 39531]

Instrumentation Type: liquid level, point

Physical Principle: acoustic, magnetostrictive

Description:

Instrument is mounted in the tank wall with a nickel rod driving a membrane. Difference in membrane vibration is sensed amplified and serves as liquid level indication. Oxygen service is inferred from [31962], as is figure 15 below. Sensors have a high resistance to shock.

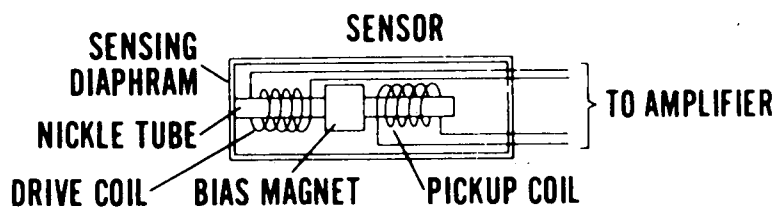


Figure 15. Magnetostrictive Liquid Level Device

An electronic method allowing compensation for effective liquid level while the transducer cools down to liquid temperature is described in [39531].

Materials of Construction: stainless steel membrane

Performance Characteristics:

liquid level resolution: $\pm 0.5\%$ of span

response time: 20 ms

Oxygen Service: Yes

Other Fluids: N_2 , H_2 , H_2O , RP-1
fuel

Limitations: sensors must be recalibrated for different liquids. Sensors are subject to cavitation in some liquids (water?).

42. Piezoelectric Transducer

Reference: [16980, 40123]

Instrumentation Type: liquid level, point

Physical Principle: acoustic, piezoelectric

Description:

The change in acoustic damping which occurs when the medium changes from liquid to vapor causes a change of energy dissipation in the resistive component of a crystal's equivalent impedance. The Q of the circuit decreases with the crystal in liquid, damping oscillations. Circuit oscillation is detected to provide an output signal. The transducers used are most often quartz crystals along with the essential electronics. The instruments tested are quite fragile, and are no longer manufactured.

Materials of Construction: quartz, lead wires

Performance Characteristics:

liquid level resolution: 0.04"

response time: 0.2 sec

Oxygen Service: No

Other Fluids: H_2 , N_2 , H_2O , RP-1
fuel

Limitations: the sensor probes are pressure sensitive and fragile

F. Forced Harmonic Oscillation

General Discussion: Several of the instruments already described, i.e., items 17 and 18 can in principle be used to sense liquid level. The application would be that of a point sensor, however, there is no indication in the available literature that these instruments have actually been so employed.

43. Vibrating Paddle

Reference: [16980, 33964]

Instrumentation Type: liquid level, point

Physical Principle: forced harmonic oscillation, paddle

Description:

The difference in viscous damping between liquid and vapor provides a variation in oscillation of a mechanical paddle which is driven by an oscillating solenoid slug. A similar slug mechanically linked to the paddle and oscillating in the magnetic field of a pickup coil produces a varying voltage that is converted to a usable output. A diagram of the device is shown in figure 16 which is taken from [33964].

Materials of Construction: not given

Performance Characteristics:

liquid level resolution: $\pm 0.1''$

response time: 1.2 sec

Oxygen Service: No

Other Fluids: H₂

Limitations: probe must be firmly mounted

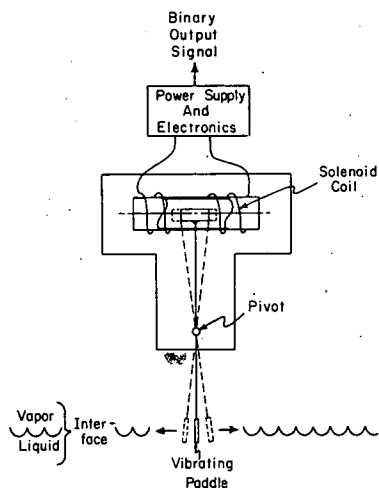


Figure 16. Vibrating Paddle Liquid Level Device

G. Liquid Level by Pressure

44. Differential Pressure

Reference: [70607, 36964, 25170, 34928]

Instrumentation Type: liquid level, continuous or point

Physical Principle: pressure, differential pressure

Description:

The gages measure the hydrostatic head of liquid by means of two pressure taps - one connected to the ullage space above the liquid, and the other to the bottom of the container, as shown in figure 17 which is taken from [70607].

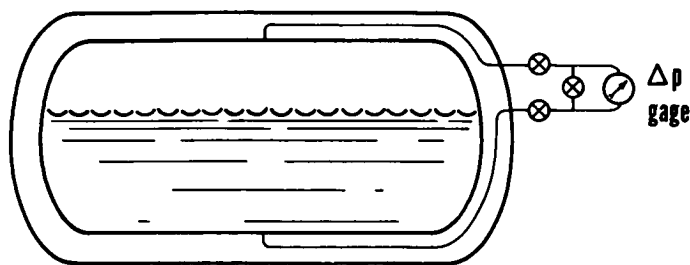


Figure 17. Liquid Level by Differential Pressure

Oxygen service can be inferred from Johansson [36151] "the ΔP type is best suited for the cryogenics of higher density, i. e. , LOX," with "little data being available regarding accuracy." Insulation for the liquid line going straight into a cryogenic vessel is best shown in [36964], a point level application of a simple tube in oxygen is given in [25170], while a control system using the differential pressure ratio of fuel/LOX is described in [34928].

Materials of Construction: copper, stainless steel, aluminum foil, mylar

Performance Characteristics:

liquid level resolution: $\pm 1\%$ of span, ± 0.5 mm in point application

response time: not given

Oxygen Service: Yes

Other Fluids: N_2 , H_2 , air

Limitations: care must be taken to set or fix the liquid-vapor interface in the

liquid leg of a cryogenic pressure measuring system, to maintain all parts of the system in a leak-free condition for true gage readings, and to avoid percolation in the line.

45. Vapor Pressure

Reference: [16720, 52068, 16910, 20855]

Instrumentation Type: liquid level, point or continuous

Physical Principle: pressure, vapor pressure

Description:

These liquid level detectors are quite similar in principle to a vapor pressure thermometer. Reference [16720] use a bellows reservoir to take up the volume of the warm gas. Liquid level in the instrument follows that in the tank. Additional details are given in [52068]. Quite similar is the device of [16910] where the height of the liquid in the capillary and its corresponding pressure is calibrated to give a continuous reading of liquid level. Details of construction for a simple device including dimensions and materials are given in reference [20855]. The pressure change liquid to gas for nitrogen is about 3 lb/in^2 .

Materials of Construction: brass, beryllium copper, copper, stainless steel
the bourdon tube of the pressure gage, and seal off valves

Performance Characteristics:

liquid level resolution: ± 1.5 mm

response time: 2 sec?, "without measurable time lag"

Oxygen Service: Yes

Other Fluids: N_2 , air

46. Gas Bubbler

Reference: [43419]

Instrumentation Type: liquid level, point or continuous

Physical Principle: pressure, gas bubbler

Description:

Quite similar to item 44 above, except that the leg that has cryogenic liquid in it is purged by a flow of gas metered to give continuous moderate bubbling from the submerged end of the tube in the tank. Reference [43419] illustrates the point level sensing application. With a sufficiently sensitive pressure gage the device can yield a continuous level indication.

Materials of Construction: not given, however they should be quite similar to item 44

Performance Characteristics:

liquid level resolution: $\pm 1\%$ of span

Oxygen Service: No

Other Fluids: N_2 , LNG

Limitations: difficult to operate on vessels under pressure

47. Mercury Sealed Bell

Reference: [75970, 49030]

Instrumentation Type: liquid level, continuous

Physical Principle: pressure, mercury sealed bell

Description:

These devices measure level changes in pressure vessels by sensing changes in hydrostatic head. They are quite similar in principle to the ordinary differential pressure device, except that they are designed to work in vessels under pressure, and that mercury is used to transmit the hydrostatic head. Reference [75970] uses a mercury column the level of which is varied by expansion and contraction of methane in the manner of a vapor pressure thermometer.

Materials of Construction: Hg, methane, others not given

Performance Characteristics:

liquid level resolution: $\pm 1\%$ of span

Oxygen Service: No

Other Fluids: CH_4

48. Diaphragm Devices

Reference: [75377, 49030]

Instrumentation Type: liquid level, point, also continuous

Physical Principle: pressure, diaphragm box

Description:

A typical oxygen application [75377] uses a closed sensing container quite similar to a vapor pressure thermometer. The accompanying pressure changes are transmitted to a diaphragm. The diaphragm is balanced against a reference pressure or its movement can be measured directly. The devices can be made to give continuous liquid level readings by adding force balancing units [49030].

Materials of Construction: 317 stainless steel, silicone fluid-sometimes

Performance Characteristics: varies widely with internal pressure of tank

liquid level resolution: $\pm 1.5\%$ @ 20 psig, 3-6% @ 150 psig, 10-18% @ 400 psig

Oxygen Service: Yes

Other Fluids: N_2 , air

Limitations: inaccurate at high static pressure

H. Liquid Level by Optical Means

49. Optical Point Level Sensor

Reference: [16980, 40123, 36151, 40167, V1637]

Instrumentation Type: liquid level, point

Physical Principle: optical (see below)

Description:

This system exploits the difference in the index of refraction between liquid and gas. The sensor is a light switch. The system consists of a light source, optical prism, solar cell, a remote miniaturized amplifier, and a relay. Light is directed down one side of the transparent probe. If there is no liquid present at the prism end of the probe, the light is reflected from the two 45° surfaces of the prism and transmitted to the solar cell. If the prism end of the probe is immersed in a liquid, the angle of refraction of the light is changed such that the light is passed into the liquid without reflection, as shown in figure 18 which is taken from [40167]. Oxygen service can be inferred from [36151]. The sensors have been used in LOX and in JP4 on the S-1C stage for Apollo. Performance as given by [V1637] has improved considerably over [16980] or [40123].

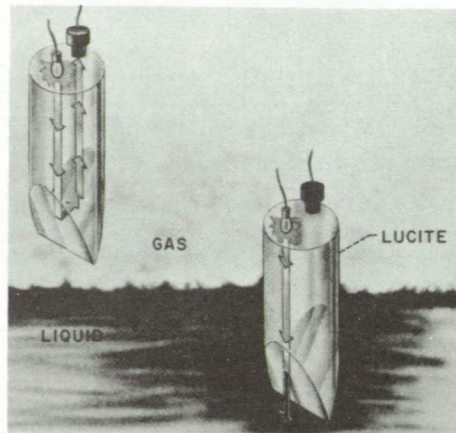


Figure 18. Optical Point-Level Sensor

Materials of Construction: aluminum, glass or lucite

Performance Characteristics:

liquid level resolution: 0.1"

response time: 50 msec

Oxygen Service: Yes

Other Fluids: H_2 , N_2 , H_2O , RP-1
fuel, JP4

Limitations: the light source causes continual boiling in liquid

I. Liquid Level with Resistance Measurements

General Discussion: Resistance probes are by nature point detectors for liquid level (a in figure 19). However, several probes can be strung together in a rake to obtain semi-continuous indication. Continuous level indication by the resistance method can be achieved with a vertical coil of wire in the tank [70607], the length of the submerged element, as determined by resistance measurement, being proportional to liquid level (b in figure 19). Another way to get continuous indication is to use some sort of drive mechanism [see for example 39525].

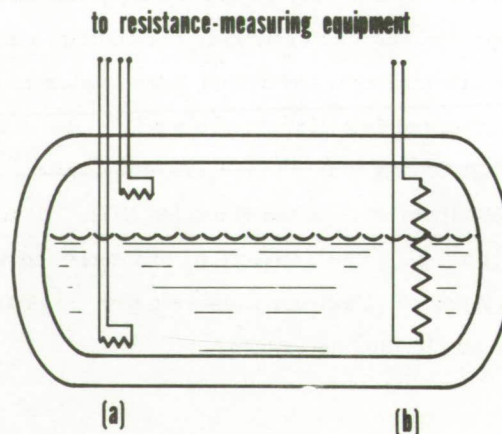


Figure 19. Liquid Level by Resistance Measurement

The resistors used as sensors fall into two general categories, metallic conductors which include the hot wire and thermocouple varieties, and semiconductors which include carbon resistors, thermistors, diodes, and transistors. Carbon thin film resistors are in this context merely another variety of carbon resistor. A review paper on multipoint level sensing, i.e., continuous liquid level, considers response time, sizing, and detector circuits for carbon resistors [67018]. The paper is applicable to He, H₂, Ne, N₂ but specifically excludes O₂. In fact, with the exception of item 51, the devices based on heat transfer have, for obvious reasons, simply not been used in oxygen service.

50. Hot Wire Devices

Reference: [75452, 58460, 37688, 39532, 16980, 24858, 33964]

Instrumentation Type: liquid level, point, and continuous

Physical Principle: heat transfer, hot wire

Description:

The discussion here is a composite of a number of sources. The most basic paper is the one by Wexler [75452]. As an example of a very sensitive arrangement we note [58460]. Design curves for a platinum sensor are given in [37688] while an example of a rake of hot wires, i.e., a continuous detector is found in [39532]. We take the performance characteristics from the testing in LH₂ [16980]. Finally we note that platinum wire can catalyze explosions of H₂ and air, especially since in the gas phase the temperature of the wire can be quite high [24858]. A typical schematic of the hot wire device is shown in figure 20 which is taken from [33964].

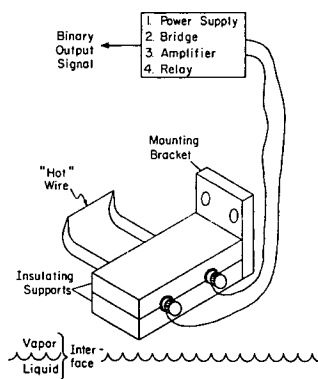


Figure 20. Hot Wire Liquid Level Device

Materials of Construction: platinum, tungsten, 72% nickel-28% iron, glass to metal seal, still well of mylar, epoxy cement, silver paint, german silver, copper, glass

Performance Characteristics:

liquid level resolution: 0.06 mm

response time: 0.2 sec

Oxygen Service: No

Other Fluids: H₂, He, N₂

Limitations: hot wire in the gas phase can be an ignition source. Gages are inaccurate if splashed with drops of liquid, or in the vent line of a cryogenic container.

51. Wire Grid Sensor System

Reference: [V1627, V1637]

Instrumentation Type: liquid level, point

Physical Principle: heat transfer, hot wire

Description:

This system utilizes a resistance sensing element consisting of a .0005 inch diameter gold plated platinum wire grid. The wire is powered by a constant current to maintain its temperature at a level slightly higher than its surrounding environment. Since the resistance of the wire varies as a function of temperature, any change in the medium in contact with the sensing element, whether liquid-to-vapor or vapor-to-liquid, causes a relatively large and almost instantaneous change in resistance.

Materials of Construction: gold plated platinum

Performance Characteristics:

liquid level resolution: $\pm 0.1''$

response time: 50 msec

Oxygen Service: Yes

Other Fluids: H₂

52. Thermocouple Devices

Reference: [52557]

Instrumentation Type: liquid level, point

Physical Principle: heat transfer, thermocouple

Description:

In cryogenic service the thermocouple device is actually the predecessor of the hot wire, see for example [75452] under item 50 above. In this device the sensitive element is a flattened Chromel-Alumel thermocouple. The element is heated radiantly producing an above ambient temperature output signal. The signal decreases when a drop in liquid level occurs. Ambient temperatures are monitored when the thermocouple is not heated. Equivalent descriptions of the device are given in [40940] and [61818]. An attached metal foil provides a heat sink. Advantage of this device is a direct voltage output from the thermocouple junction rather than a resistance measurement.

Materials of Construction: chromel-alumel wire, inconel foil, platinum wire
stainless steel, silicone compound

Performance Characteristics:

liquid level resolution: not given

response time: 0.15 sec

Oxygen Service: No

Other Fluids: N₂

Limitations: as in item 50

Reference: [25843, 28882]

Instrumentation Type: liquid level, point, and continuous

Physical Principle: heat transfer, thermocouple

Description:

In [25843] two thermocouple junctions are used in order to get extreme accuracy in liquid level. In [28882] the thermocouple sensing element is used to give a simple continuous indication of liquid level.

Materials of Construction: iron/gold-Chromel, epoxy, German silver, copper-constantan

Performance Characteristics:

liquid level resolution: ± 0.001 cm point, ± 0.1 cm continuous

response time: 10 min on refilling for continuous indication

Oxygen Service: No

Other Fluids: He, N₂

Limitations: on accuracy, is the roughness of the liquid whose level is required

53. Semiconductor Devices

Reference: [16980, 75261, 40900, 51043, 61819, 40436, 64468]

Instrumentation Type: liquid level, point, and continuous

Physical Principle: heat transfer, semiconductor

Description:

This section is again a composite of a number of sources. Carbon resistor point sensors were tested in LH₂ [16980], an example of a string of these sensors is given in [75261]. Diodes, thermistors, or transistors are used in a number of applications, mostly in liquid nitrogen, for example, in [40900] a silicon diode has a response time of 0.1 sec a volume of 1.2 mm³ and a power dissipation of 4 mW. A similar application of a silicon diode is given in [51043], while a string of diodes is described in [61819]. Thermistors were tested in LH₂ [16980]. Response time of these sensors going from liquid to gas can be improved by the addition of a heater [40436]. A novel use of carbon thin film sensors for phase discrimination in low "g" environment is still in

the experimental stage of development [64468]. In this application the sensor is used for both phase discrimination and temperature indication. A power step is applied to the sensor, and the time required to reestablish thermal equilibrium is monitored [51008].

Materials of Construction: graphite, plastic covers, lead wires, silicon, sapphire

Performance Characteristics:

liquid level resolution: 0.02" thermistor, 0.06" carbon resistor

response time: 0.4 sec carbon resistor, 1 sec thermistor

Oxygen Service: No

Other Fluids: H₂, N₂

Limitations: sensors can be damaged if subjected to excessive heating

J. Liquid Level by Thermal Expansion

54. Differential Thermal Expansion

Reference: [29716, 40844]

Instrumentation Type: liquid level, point

Physical Principle: differential thermal expansion (see below)

Description:

The difference in thermal expansion between metal and glass is employed to provide a proportional level control. The same principle is used in [40844] to make a simple on-off control.

Materials of Construction: copper, brass, stainless steel, pyrex, silver solder, epoxy

Performance Characteristics:

liquid level resolution: ± 2 mm

Oxygen Service: No

Other Fluids: N₂

5. Summary and Recommendations

In the course of this survey we have looked at a total of 480 documents which potentially contained information applicable to density or liquid level instrumentation for oxygen. The large number of references has been reduced to 122 which either apply directly to oxygen, or to a surrogate fluid such as nitrogen or hydrogen. If the latter, then in the opinion of the reviewer the technique can be applied, albeit with modifications, to oxygen. The initial 480 documents contain about 20 distinct instruments which have actually been used in oxygen service, as shown by instrumentation type in table 5. The rather low total of densitometers is surprising. It prompted a hasty survey of instrument manufacturers with nearly identical results. We contacted 20 commercial manufacturers of instrumentation equipment who had advertised in trade journals such as Cryogenics and Industrial Gases, LNG/Cryogenics, Cryogenic Technology, etc. We asked for liquid densitometers qualified

for oxygen service. The responses were: no densitometers 11; no response 8; densitometer yes, but oxygen qualified no 1. The first conclusion would be that either there are no off-the-shelf densitometers available, or that the few pinpointed in this report are not advertised in the standard cryogenic publications.

Table 5. Instruments with Demonstrated Oxygen Service

Instrumentation Type		Item Number in Section 4									
Density	static density	2	4	9	10	16	17				
	dynamic density	2				16	17				
	low or zero "g" density									20	
	very low density									15*	
	supercritical density		4								
Liquid Level	point sensors	4	26	33	35	41	44	45	48	49	51
	continuous sensors		27	37	40		44	45	48		

* air

5.1 Techniques That Should be Exploited

Several experimental techniques look most promising and worthwhile; and research in these areas should be continued. Several other experimental techniques which have not yet been applied to densitometry, liquid level measurement or phase detection of liquid oxygen appear to have reasonable promise of success. Therefore, it is strongly recommended that research be continued on:

- RF gaging of highly stratified liquids and liquids of non-uniform density with eventual application to zero "g" [V1634],
- microwave gaging, both FDR and TDR, for both densitometry and liquid level detection [72638, 73600],
- carbon thin film transient monitoring for both temperature determination and phase discrimination [51008]; and

it is recommended that the following experimental techniques be investigated for applicability to densitometry and liquid level detection:

- optical attenuation for densitometry,
- index of refraction for liquid level, densitometry or phase detection,
- light scattering in the critical region for densitometry or phase detection, and
- addition of radioactive tracer materials to liquid oxygen, such as already done for xenon [53410], for densitometry.

5.2 Problem Areas in Density and Liquid Level Instrumentation

Each document surveyed in this report was addressed to a particular problem of instrumentation. It seemed worthwhile to recapitulate the major problem areas. When faced with a choice of density or liquid level instrumentation for an application to oxygen consideration of the elements below will help to make a decision. The various problem areas are grouped under the headings of tank volume, ullage problems, general considerations, density considerations, and liquid level considerations. As an aid to the user we point out that besides the instruments listed in this volume additional listings of commercial instruments are given by Considine [49030] and Hayakawa [V1637].

Tank Volume

As explained earlier, quantity gaging is accomplished either by combining a density measurement and a volume, or a liquid level measurement with an inferred density and a volume. In either case a volume determination is required. This requirement that the volume be known is so universal that it is hardly ever stated explicitly. Nevertheless, obtaining a cryogenic volume offers several obstacles. The question is, how is the volume obtained? From tank strapping? By calculation? Has the tank shrinkage from thermal contraction been calculated? Does the tank deform under static load? Is there additional deformation from a dynamic load?

Ullage Problems

The vapor space above the liquid in a cryogenic tank is called the ullage. Heat leak into the container and gas used to pressurize it can cause gaging problems which are gathered here under ullage problems.

Reference [31846] considers the gradual and general warming of a tank such as an over the road oxygen unit. The tank is filled at atmospheric pressure to a particular level called "trycock." Considerable ullage is available above the liquid. Some time later after the tank has warmed the inside temperature and pressure are much higher, and the liquid has expanded considerably above the trycock level. Specific conditions for the oxygen example are 1 atm and 71.3 lb/ft³, and 150 psig and 59.3 lb/ft³. A differential pressure gage would read full in either case since it is sampling hydrostatic head, and while the density has changed, the liquid height has changed too. A liquid level indicator, however, would show about a 17% change in quantity, "overfull," leading to a potential error unless the density change is specifically taken into account.

Reference [12161] considers the case of a capacitance gage when the ullage is pressurized. As the pressure changes in the vapor space the density, and therefore the dielectric constant, of the vapor changes. Since the instrument is normally calibrated at the normal boiling point measurement errors can be introduced if pressurization of the ullage is

not correctly accounted for. Tables of values are given for a 50' tank of liquid hydrogen. In the most extreme case a 5' error in liquid level is calculated when the tank is nearly empty with a pressurization of 100 psia.

Occasionally the ullage temperature rises above the temperature of the liquid. In this case the temperature distribution along the cylinders of a capacitance gage can be different from that along the walls of the tank giving rise to a "manometer" effect illustrated in reference [49055]. Different measurement errors are possible depending on whether the outer capacitance tube is in one piece, or whether it is relieved with holes to promote circulation.

Finally, reference [V1637] indicates that the standard coaxial cylinder capacitance system is subject to capillary rise under low gravity conditions. The capillary rise for LOX is on the order of 20" for capacitance sensors similar to those used in the Saturn S-II stage.

General Considerations

Normally the selection of an instrument is based on reliability, ruggedness, simplicity, sensitivity, accuracy, and cost. In addition to those one should consider:

1. Oxygen compatibility
2. Are two phases liquid-gas likely to be present? Gas bubbles due to boiling?
3. Is tank stratification or roll-over likely to be a problem?
4. Would it be preferable to have no moving parts?
5. Would it be preferable to have no liquid or gas flow?
6. Are there other limitations, for example, radiation hazard, complicated electronics?

Density Considerations

1. Is the sample taken representative of the density?
2. In flow problems rapid response and wide range in density are desirable. Are there any viscosity (drag) effects? Would it be preferable to have no intrusions into the flow stream?

Liquid Level Considerations

1. How is the density obtained? Measurement? Pressure and/or temperature and data tables?
2. Should the instrument be inside the tank? See ullage problems above.
3. Are splashing, boiling, tank distortion, transfer-in of liquid likely to be a problem?
4. Hydrostatic pressure gages are subject to oscillation and percolation.
5. Hot wire instruments can become incandescent [39027].
6. For large oxygen tankage we may wish to adopt the recommendations for large LNG tanks [67349, 84996].

In that application it is recommended that the liquid level gages be replaceable without taking the tank out of operation. Also recommended are a second liquid level gage for backup, a device to prevent overfilling, and a low level alarm.

5.3 Recommendations

Instrumentation Development

In surveying the literature one is struck by how little of the space hardware is actually used in the commercial sector. A deliberate effort to develop space age instrumentation for commercial and industrial applications seems to be worthwhile. An example that comes to mind immediately is a large scale densitometer/flowmeter for LNG applications. Development of other items could be based on the experimental techniques presently not used (section 5.1), especially the RF gaging technique. Another experimental effort should be directed at the problem of overflow on tank filling, surely one of the more substantial safety hazards with liquid oxygen.

Instrumentation Description

From the survey it is evident that the terms precision and accuracy are often used interchangeably. Seldom is accuracy expressed in terms of a standard deviation σ with known or expressed confidence limits. A quick perusal of the report will show how much more often these terms are absent. In addition, for different applications different items of information are desired. For example, in the survey conducted by Hayakawa [V1637] the items of interest were: accuracy, temperature range, pressure range, power requirement, and response time. For other applications weight, size, or some other parameters may be the determining factor. A cooperative effort involving the American Society for Testing and Materials, the Instrument Society of America, the Compressed Gas Association, the National Aeronautics and Space Administration, and the National Bureau of Standards is suggested. A minimum list of parameters should first be agreed upon, and then the descriptive reporting, especially of instrumentation errors, can be standardized.

Calibration Facility

Primary instruments to calibrate either densitometers or liquid level devices do not exist. At present, with considerable expense, testing is conducted in-house, see for example the oxygen tankage weighing system described in reference [29478]. It is appropriate for the Department of Transportation, the National Aeronautics and Space Administration, and the National Bureau of Standards to support a calibration facility for devices operating in liquid oxygen, and also to develop a density transfer standard that would provide traceability to NBS.

Measurement Approach

Instrumentation recommendations or requirements for oxygen storage systems should be reviewed. For example, the recommendation of diptube or differential pressure gage for loading control on liquid oxygen road tankers in CGA standard 341^{*} [V1641] is insufficient. A positive control on filling, and in particular over-filling should be provided. A cooperative effort is suggested between industry, the Compressed Gas Association, the Department of Transportation, the Interstate Commerce Commission, the National Aeronautics and Space Administration, and the National Bureau of Standards to determine what the requirements are, and what the measurement approach should be. A recent effort by the American Gas Association to prepare a measurements manual for LNG [V1640] illustrates the type of effort suggested.

Zero Gravity

In spite of considerable effort to develop viable systems for the zero or low "g" environment of space the recommendation to "develop a reliable and accurate zero g quantity measuring system" is still with us [82180]. RF gaging mentioned in section 5.1 should be pursued as the most promising experimental approach.

Acknowledgment

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* The June 1972 addendum makes this a standard. The word tentative has been deleted. Also, cryogenic road tankers are still approved on an item by item basis.

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